nature plants

LETTERS

PUBLISHED: 1 MARCH 2017 | VOLUME: 3 | ARTICLE NUMBER: 17012

The environmental impact of fertilizer embodied in a wheat-to-bread supply chain

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Food production and consumption cause approximately one-third of total greenhouse gas emissions[1–3], and therefore delivering food security challenges not only the capacity of our agricultural system, but also its environmental sustainability[4–7]. Knowing where and at what level environmental impacts occur within particular food supply chains is necessary if farmers, agri-food industries and consumers are to share responsibility to mitigate these impacts[7,8]. Here we present an analysis of a complete supply chain for a staple of the global diet, a loaf of bread. We obtained primary data for all the processes involved in the farming, production and transport systems that lead to the manufacture of a particular brand of 800 g loaf. The data were analysed using an advanced life cycle assessment (LCA) tool[9], yielding metrics of environmental impact, including greenhouse gas emissions. We show that more than half of the environmental impact of producing the loaf of bread arises directly from wheat cultivation, with the use of ammonium nitrate fertilizer alone accounting for around 40%. These findings reveal the dependency of bread production on the unsustainable use of fertilizer and illustrate the detail needed if the actors in the supply chain are to assume shared responsibility for achieving sustainable food production.

A projected human population of 10 billion[10] and an increasing consumption of food that has high environmental impact associated with economic development[11] are placing massive strain on the global agri-food system. Meeting the challenge of achieving sustainable food security requires consideration of all the key aspects of food production and consumption, taking a holistic agri-food ecosystem approach that includes land and resource use, crop production, consumer behaviour and human health[7]. Moreover, for a condition to materialize in which collective action and shared responsibility occurs within fragmented food supply chains, an integrating framework that involves the mapping, analysis, visualization and sharing is needed[7]. Integration can be enabled through supply chain sustainability research, which yields total visibility of the entire supply chain[9,12,13]. To realize this ambition, a natural resource-driven business experiment involving a mixed methods approach of quantitative analytical modelling and qualitative contextualization was deployed to develop a detailed case study of environmental impact in the manufacture of a specific foodstuff, a loaf of wholemeal bread. This involved LCA at each stage of the supply chain for the loaf of bread.

It is well known that the more precise are the sources of data for an LCA model, the more accurate are the results from the LCA modelling. Most of the existing LCA research relies on both primary and secondary data, the latter used to compensate for the unavailability of primary data. Consequently, an artificial level of uncertainty in the data averages out the variation hence making the environmental impact from a modelled supply chain a proxy and an estimate, as in all previous LCA of the wheat–bread supply chain[14–17], where primary data might be used for one process stage but secondary data for others (for example, ref. 17). To address this deficiency, and in contrast to all previous studies, we utilized primary data at all stages of the linked Cradle to Gate UK bread manufacturing life cycle, with 90% of the process stages modelled on the basis of primary data. This was enabled by collaboration with a commercial bread and flour producer and a large agronomy services provider. The higher level of granularity achieved in this way increases the confidence level of the results and therefore the certainty and validity of the conclusions on which action is based.

Three supply chain stages were considered (Fig. 1): wheat cultivation, which includes ground preparation, sowing the wheat seed, application of agrochemicals, harvesting of the wheat grain, drying, storage and finally transportation to the mill; milling, which includes the transformation of cultivated wheat grain into wholemeal flour, through intake, cleaning, milling and out-loading processes before transportation to the bakery; and baking, which comprises all the remaining processes leading to the final, packaged loaf of wholemeal bread. Primary data for material and energy flow were collected for the designated 14 processes at these three stages of the supply chain, calibrated to a functional unit, a single wholemeal loaf of bread weighing 800 g (Supplementary Figs 1–3). Each loaf required cultivation of 7.2×10^{-5} hectares or 0.72 m^2 of land. This produced 688 g of grain, using a number of fertilizer inputs: 42.0 g of granular ammonium nitrate (580 kg ha^{-1}), 11 g of triple superphosphate (152 g ha^{-1}), 6 g muriate/sulfate of potassium (83 kg ha^{-1}) and 3 ml of liquid ammonium nitrate (41 l ha^{-1}, applied just before harvest to maximize protein content of the grain). On transfer to the mill, there are two key output streams. Firstly, a small proportion of the grain (about 3%) is rejected on delivery if it fails to meet strict quality standards concerning excess moisture, the presence of foreign bodies or contamination. Secondly, around 22% of wheat grain is lost during the extraction process; this loss accounts for the difference in mass between raw, dirty wheat and flour leaving the mill, after excess moisture and non-millable impurities are removed. During milling a total of 520 g of flour is produced in processes consuming ~0.07 kWh electricity. Before baking a number of ingredients, including 365 g of water and 13 g of sugar, were added to the flour to give a mass of 950 g. A further 5.8% loss of solid flour because of suboptimal quality reduced this mass to 898 g; the final preparation and the baking process resulted in 3.5 g of flour loss and reduction in mass to 807 g through water evaporation. The electricity consumed at the bakery was 0.09 kWh.

The raw data were analysed using the Supply Chain Environmental Analysis Tool's (SCEnAT) LCA methodology[9]. To provide a broad assessment of environmental impact on air, water and land, six

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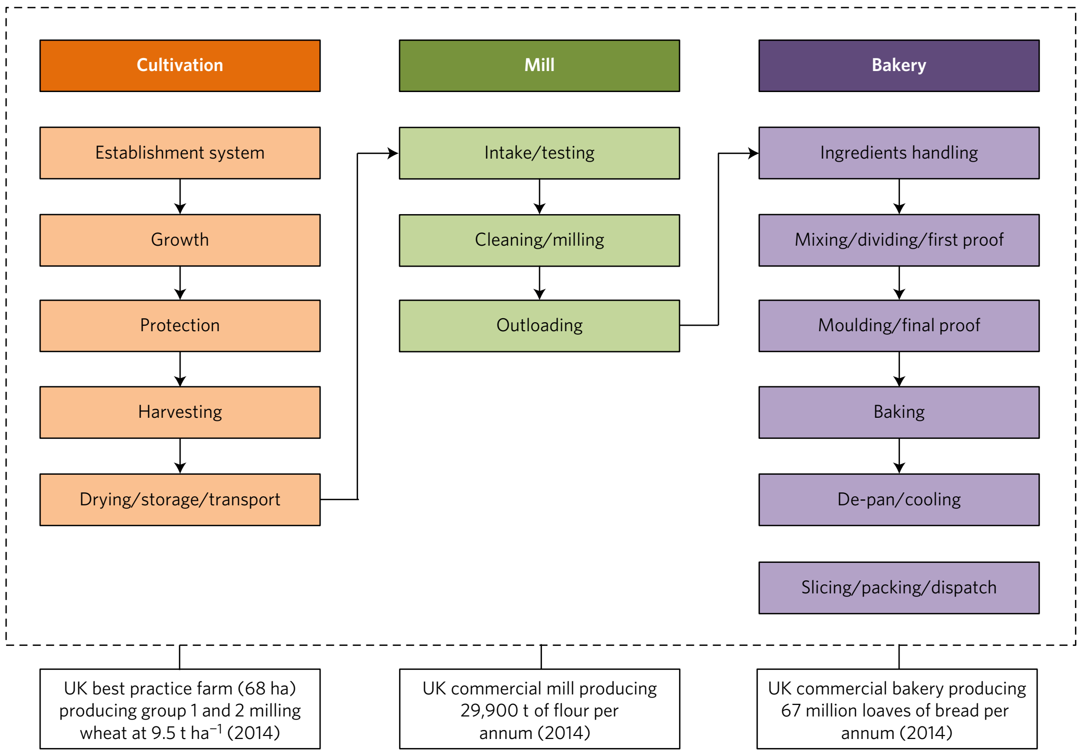
a



b

Supply chain stage	Process stage	Material and energy inputs analysed
Cultivation	Establishment system	Machinery/energy for tillage, drilling and rolling, pre-seed herbicide and application, water, wheat seed
	Growth	TSP fertilizer, MOP/SOP fertilizer, granular ammonium fertilizer, liquid ammonium fertilizer, application
	Protection	Lambda-cyhalothrin insecticide, crystal herbicide, glyphosate herbicide, SDHI fungicide, water, application
	Harvesting	Machinery/energy for harvesting
	Drying/storage/transport	Tractor and trailer, energy to dry wheat grain, lorry (29 t)
Mill	Intake/testing	Gas, electricity
	Cleaning/milling	Gas, electricity
	Outloading	Gas, electricity
Bakery	Ingredients handling	Yeast, water, WMSSL blend, sugar, gluten, salt, improver, freshener, gas, electricity
	Mixing/dividing/first proof	Gas, electricity
	Moulding/final proof	Rapeseed oil, gas, electricity
	Baking	Gas, electricity
	De-pan/cooling	Tin release agent, gas, electricity
	Slicing/packing/dispatch	LDPE bag, tape paper, tape gold, ribbon, gas, electricity

Figure 1 | The wheat-to-bread supply chain. a, A map of the supply chain showing cultivation, mill and bakery stages. Sources of energy/material flow data from two industry partners are also shown. These sources are a large commercial bread maker with multiple production sites across the UK and a wheat farm that produced group 1 and 2 milling wheat at 9.5 t ha^{-1} during the 2014 harvest. **b**, Supply chain stages and their component processes. TSP, triple superphosphate; MOP, muriate of potash; SOP, sulfate of potash; SDHI, succinate dehydrogenase inhibitor; WMSSL blend, blend of fermented wheat flour, wheat gluten, soya and sodium stearoyl lactylate; LDPE, low-density polyethylene.

contrasting impact categories were selected for analysis; these are expressed as 'potential' impacts. Thus, for example, emission of greenhouse gases is quantified as global warming potential (GWP), the eutrophication potential (EP) is a measure of pollution of water courses and human toxicity potential (HTP) quantifies the potential human health problems caused by release of toxic substances into the environment.

GWP data calculated for each supply chain process are shown in Supplementary Figs 3–6. GWP from the whole supply chain was found to be 0.589 kg CO_2 equivalent (CO_2e) per loaf of bread, and it is clear immediately that wheat cultivation is the major source; this supply chain stage totalling 0.388 kg CO_2e, with the growth and protection process stages (mostly fertilizer) alone

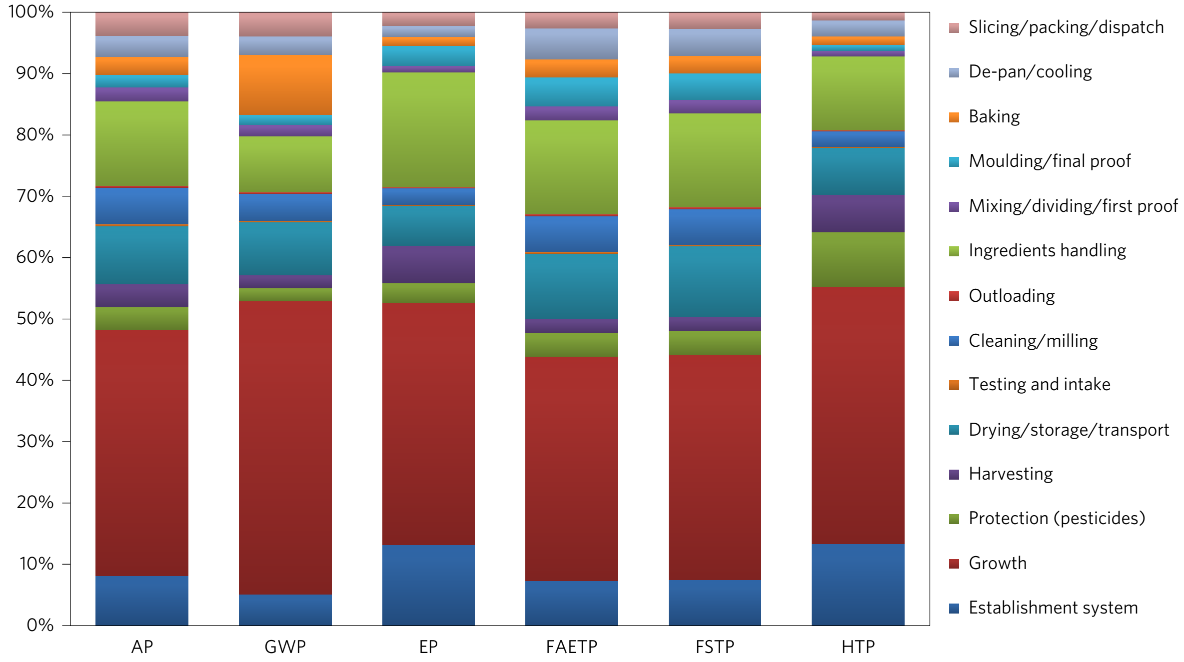


Figure 2 | Process group environmental impact. Each coloured bar section represents the environmental impact of process groups at cultivation, mill and bakery stages as shown in Fig. 1, expressed as a percentage of the total values. Material and energy input data were assessed alongside six impact categories selected from the CML (2001)[35] environmental impact categorization model produced by the Institute of Environmental Sciences (CML) at Leiden University. AP, acidification potential; GWP, global warming potential; EP, eutrophication potential; FAETP, freshwater aquatic ecotoxicity potential; FSTP, freshwater sediment toxicity; HTP, human toxicity potential.

accounting for 0.281 kg CO_2e. Milling added a further 0.028 kg CO_2e and the bakery stage 0.173 kg CO_2e.

Impacts from each process in the supply chain were added together to give their cumulative environmental impacts, expressed as a percentage of the total in Fig. 2. All the processes involved in cultivation of wheat account for 65.8% of the total GWP, which is within the range of previous analyses using secondary data sets[14–16]. Similarly, wheat cultivation was the principle cause of the other environmental impacts: 68.5% EP and 77.9% HTP. The fertilizer used to promote growth of the wheat crop was found to be the largest single process contributing to environmental impact metrics (red bar in Fig. 2), for example accounting for 47.8% GWP, 38.5% EP and 41.9% HTP.

Other processes involved in cultivation had significant, but lesser impacts. The use of farm machinery in preparation of land accounts for 5.2% of total GWP. Grain drying is another significant cultivation hotspot; farmers are normally contracted to deliver wheat grain for storage with a water content lower than 15% to pass the weight and pricing thresholds expected by the buyers. In our study, electric continuous flow grain dryers were used to reduce water content. Grain drying, storage and transport to the mill together account for 8.7% of GWP, 6.5% of EP and 7.6% of HTP, respectively.

Baking, ingredients handling and cleaning/milling were found to be significant GWP hotspots, accounting for 9.7, 9.1 and 4.4% respectively. Energy is the key contributor to GWP in milling and baking processes. In particular, gas usage during baking accounted for 7.9% of overall GWP. Similarly, electricity usage during cleaning/milling, mixing/dividing/first proof, baking and de-pan/cooling stages were identified as significant hotspots, contributing 4.2, 1.6, 1.8 and 2.2% to overall GWP, respectively. These processes contribute to ET and HTP to similar extents.

The upstream supply chains of various ingredients added to flour to form bread dough during the ingredients handling stage of baking also contributed to GWP, the most significant being wheat gluten, sodium stearoyl lactylate, fermented wheat flour and sugar which accounted for 2.6, 1.5, 1.5 and 1.1% respectively. The switch to the use of low-density polyethylene (LDPE) wrapping has reduced the environmental burden of bread packaging compared with more traditional plastic packaging types. However, packaging is still a notable contributor to GWP (3.1%).

This study highlights the contribution of fertilizer to the environmental impact of bread production. Remarkably, the use of ammonium nitrate fertilizer alone accounts for most of this, 0.256 kg CO_2e, 43.4% of overall GWP (Fig. 3). Similarly, 34.1% of EP and 32.5% of HP are due to ammonium nitrate. This value of GWP measures the CO_2 emissions associated with the manufacture and application of the fertilizer and N_2O released into the atmosphere from the on-farm degradation of ammonium nitrate by soil microbes.

The exact amount of GWP from N_2O release depends of a variety factors and its estimation is the subject of some controversy[18]. Previous studies with maize[19] and wheat[20] have estimated it to be of similar proportions to the GWP arising from energy use during manufacture. We calculated 0.083 kg CO_2e per loaf arising from N_2O emissions (see Supplementary data Fig. 4), about one-third of the total. The other environmental impacts of the use of this fertilizer have been described[21], eutrophication of water courses in particular. Their quantitative significance in the wheat-to-bread supply chain is made clear in our study.

Nitrogen use efficiency (NUE) of wheat yield, defined as the ratio of harvested nitrogen to that applied to the field ultimately determines the environmental impact of nitrogen fertilizer. In our study, NUE was estimated to be 71%, in line with that predicted for the 246 kg N ha^{-1} fertilizer application used[22], which is slightly above the UK average, and typical of intensified production. Studies show that although wheat yield increases with higher applications of fertilizer, NUE declines[22]. However, without such intensive fertilization there is lower yield, and a small but important reduction in the protein content of the grain. Consequently, the cost of a staple food item made from UK wheat could rise. Alternatively, in a global wheat market, the environmental impact of fertilizer use could be 'exported' via the import of cheaper grain from other countries. Clearly neither

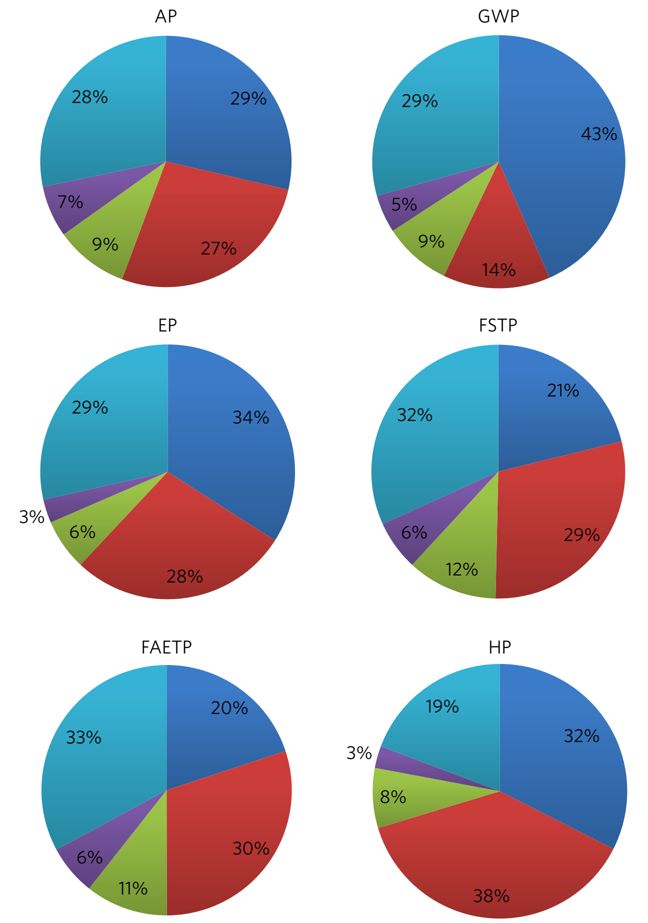


Figure 3 | Environmental impact of ammonium nitrate fertilizer in comparison to other process groups. The data for process groups were aggregated to give total impacts for ammonium nitrate (blue), and the cultivation (minus ammonium nitrate) (red), milling (purple), baking (cyan) and storage/transport (green) stages as in Fig. 1. The six environmental impact categories are as described in Fig. 2.

of these scenarios is desirable; instead, new solutions are needed[23]. These solutions can take place at different parts of the extended supply chain, from fertilizer manufacture to bread consumption.

More energy-efficient methods of synthesizing ammonium nitrate fertilizer would be beneficial (but presently seem unlikely), as would be a shift towards carbon neutral energy supply. But the most immediate solutions to the fertilizer problem mostly reside in increasing NUE while maintaining high yield[21], through a combination of improved agronomic practice and improved crop plant physiology. To reduce on-farm fertilizer use, there needs to be a move away from blanket fertilizer application towards area-specific and temporal-specific application of fertilizer[23], acknowledging the soil variation across different parts of the crop field and the differing physiological requirements for nitrogen at different stages of crop growth. More radical is a shift away from chemical fertilizer altogether towards a biological approach to nitrogen fertilization, such as crop rotations with nitrogen-fixing legumes[24] and restoration of the soil microbe/plant root interactions that promote plant growth[25]. In fact, judicious use of fertilizer incorporated into a series of such modified agronomic practice drastically reduced GWP of wheat cultivation in Canada[20]. Development of new wheat varieties with an increased intrinsic NUE could also make a significant contribution, although there are significant challenges to achieving this goal[26], either an increased ability to take up nitrogen from the soil[27] or an altered physiology that allows more biomass accumulation per unit of taken-up nitrogen[28] and allocation of more biomass nitrogen to the grain[29]. Biological nitrogen fixation by the wheat plant itself remains an important, if elusive, goal[30]. One possible consequence of maintaining wheat yield while reducing or eliminating fertilizer use could be a reduction in the protein content of the wheat grain. At present, the protein content of wheat grain used in flour production forms a key aspect of the commercial contract. For UK bread-making, a high protein content of 11–13 g per 100 g is required, a higher amount being needed for wholemeal loaves (which account for ~10% of the UK market) than for white loaves (~80% of the UK market). The wheat grain protein requirement for wholemeal bread in the current study is 13 g per 100 g. An important part of the solution to the fertilizer problem could be a change in bread-making technology to accommodate grain with lower protein content[31].

Much research takes a generic approach to identifying the interventions needed to deliver sustainable food security. Extending beyond this, our study points to the increased granularity of the information that is required to make accurately informed decisions about individual food supply chains. As argued previously, this information has to be integrated and applied across the entire supply chain[7], otherwise time, effort and resources will be wasted implementing changes of little overall significance while ignoring the real problem, in this case study, the use of fertilizer. So, having identified the problem, responsibility for implementing any or all of the above solutions must be designated. According to the principles of extended producer responsibility, all the actors in the supply chain have to share responsibility[8]. Similarly, such responsibility must be extended to the consumer. Thus although the fertilizer manufacturer may bear the biggest responsibility, actions have to be coordinated across the wheat–bread supply chain, between the fertilizer manufacturer, the farmer, the mill, the bakery, the retailer and the consumer. This new direction is feasible due to increasingly advanced data capture and sensor technology where LCA will be a norm for all decision-making across the supply chain.

The dependency of delivering high yields of high protein bread wheat on unsustainable amounts of fertilizer exposes an unresolved grand challenge for the twenty-first century: how to produce more food but with lower pollution[32]. Our findings bring into focus a key part of this challenge, resolving the major conflict embedded in the agri-food system, whose primary purpose is to make money not to provide sustainable global food security[33]. High agricultural productivity, necessary for profit for farmers, agri-businesses and food retailers, while also keeping prices low for consumers, currently requires high levels of application of relatively cheap (and often subsidized) fertilizers. The environmental impact of fertilizer use is not costed within the system and thus, there are currently no effective incentives to implement of any of the solutions described above[32].

Methods

Data collection. A LCA methodological approach was used to evaluate the environmental impact of commercial bread production in the UK, using 100% group 1 and 2 domestic milling wheat. The functional unit is defined as a single wholegrain loaf of bread, weighing a total of 800 g and the scope of the study is from Cradle (farm) to Gate (shipping of the final, packaged loaf of bread to a retailer). All agricultural and production stages are based in the UK and data is representative of the 2014 wheat harvest and production period. The supply chain was segmented into three distinct stages: cultivation, milling and baking. Primary data were collected at each of these stages, with a leading UK commercial bread manufacturer providing access to milling and bakery data sets and a large agronomy organization providing access to farm level data, using the example of a farm producing UK group 1 and 2 milling wheat at 9.5 t ha^{-1}. Data collection was undertaken through both field interviews and analysis of organizational data sets, which in combination provided researchers with a detailed understanding of energy and material flows through each of the defined three model stages. For mill and bakery stages, data were obtained for two specific sites that represented an average energy and material consumption balance for the partner's annual production; these were in Bradford and Manchester, respectively. At a farm level, material, machinery and energy data, provided in collaboration with a large agronomy organization, have been modelled from an upper quartile farm in terms of yield and agricultural efficiency.

Environmental impact categories. LCI data for all identified material and flows were sourced from the Ecoinvent database (v3.2)[34]. The Ecoinvent database provides well-documented LCI process data for a large number of materials and products covering relevant environmental flows, such as resource extraction, land use and emissions, as well as all material and energy inputs and products of an activity. To provide a broad assessment of the environmental impact that UK commercial bread production has to air, water and land, six impact categories were selected for analysis from the Institute of Environmental Sciences (CML) (2001) categorization model available in Ecoinvent, produced at Leiden University[35]. These are acidification potential (kg SO_2e, European average), climate change (kg CO_2e, GWP 100a) and eutrophication potential (kg NO_xe, European average). The various toxicity indicators use the reference unit, kg of 1,4-dichlorobenzene equivalent (1,4-DCB), and are freshwater aquatic eco-toxicity (kg 1,4-DCBe, FAETP 100a), freshwater sediment toxicity (kg 1,4-DCBe, FSTP 100a) and human toxicity (kg 1,4-DCBe, HTP 100a).

Data analysis. Domestic LCI data were prioritized for material and energy flows throughout the three stages where available. However, it was necessary to use European or global reference LCI data for some inputs. Moreover, where specific LCI data were not obtainable for a given material or process, appropriate 'closest match' substitutes were identified, in collaboration with industry partners whenever possible. Allocation was necessary at both mill and bakery stages, where, for example, several types of flour are produced at the same mill or energy flows are measured across multiple processes. Again, as with data substitution, where necessary, allocation was carried out through dialogue with industry partners to maximize accuracy. Our analysis considers output from milling and bakery stages as co-products, rather than traditional wastes as they are sold for use in other industries. Owing to the varied use of these outputs, coupled with fluctuating market pricing, we did not consider economic allocation to be appropriate in this instance. Instead, a traditional mass allocation approach was adopted in keeping with the finding that for external communication to the market and consumers, mass allocation should be viewed as the preferred method in most cases[36].

Data were combined and analysed using SCEnAT developed by researchers at the University of Sheffield. SCEnAT employs LCA methodology[9] to assess product supply chains, capturing both direct and indirect/embodied emissions in accordance with ISO14040[37] and ISO14044[38] standards. Nitrogen use efficiency was calculated using the quality-control grain protein content used by the manufacturer and a wheat grain nitrogen/protein conversion factor of 5.81[39]. On farm N_2O emissions were calculated using established protocols[40,41] as summarized in ref. 42.

Data availability. The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information files.

Received 1 June 2016; accepted 25 January 2017; published 1 March 2017

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Acknowledgements

We thank the Grantham Foundation for the Protection of the Environment for their generous support. L.G. was supported in part by Impact, Innovation and Knowledge Exchange (IIKE) funds from the University of Sheffield and pump priming funding from the P[3] Centre. We also gratefully acknowledge the support of our commercial partners.

Author contributions

P.H. and S.C.L.K. conceived the study, R.B. negotiated with the commercial partners and L.G. carried out the collection and analysis of the data. All authors were involved in the interpretation of the findings and the writing of the paper.

Additional information

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How to cite this article: Goucher, L., Bruce, R., Cameron, D. D., Lenny Koh, S. C. & Horton, P. The environmental impact of fertilizer embodied in a wheat-to-bread supply chain. *Nat. Plants* **3**, 17012 (2017).

Competing interests

The authors declare no competing financial interests.